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Limits to Cloud Susceptibility

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Abstract:

1-km AVHRR observations of ship tracks in low-level clouds off the west coast of the U.S. were used to determine limits for the degree to which clouds might be altered by increases in anthropogenic aerosols. Hundreds of tracks were analyzed to determine whether the changes in droplet radii, visible optical depths, and cloud top altitudes that result from the influx of particles from underlying ships were consistent with expectations based on simple models for the indirect effect of aerosols. The models predict substantial increases in sunlight reflected by polluted clouds due to the increases in droplet numbers and cloud liquid water that result from the elevated particle concentrations. Contrary to the model predictions, the analysis of ship tracks revealed a 15-20% reduction in liquid water for the polluted clouds. Studies performed with a large-eddy cloud simulation model suggested that the shortfall in cloud liquid water found in the satellite observations might be attributed to the restriction that the 1-km pixels be completely covered by either polluted or unpolluted cloud. The simulation model revealed that a substantial fraction of the indirect effect is caused by a horizontal redistribution of cloud water in the polluted clouds. Cloud-free gaps in polluted clouds fill in with cloud water while the cloud-free gaps in the surrounding unpolluted clouds remain cloud-free. By limiting the analysis to only overcast pixels, the current study failed to account for the gap-filling predicted by the simulation model. This finding and an analysis of the spatial variability of marine stratus suggest new ways to analyze ship tracks to determine the limit to which particle pollution will alter the amount of sunlight reflected by clouds.

1. Introduction

The primary goal of this research was to analyze a statistically large number of "ship tracks" to determine how changes in cloud droplet radii induced by ships are linked to changes in the cloud visible optical depths, and possibly cloud altitudes. How the changes are related to the *pre-existing droplet radii, optical depths, and altitudes*, as deduced from comparisons with the nearby unperturbed clouds, indicates whether cloud liquid water amounts remain reasonably fixed while droplet numbers increase and radii decrease. Increased particle pollution is an expected byproduct of burning fossil fuels. The increase in particle concentration in turn gives rise to clouds with larger numbers of droplets but the droplets are smaller. For constant liquid water amounts, these polluted clouds are expected to reflect more sunlight than their unpolluted

counterparts. In addition, models also predict that with smaller droplets, the formation of drizzle is inhibited in the polluted clouds thereby allowing their liquid water content to increase. With larger amounts of liquid water, cloud lifetimes also increase. The net effect, according to the models, is almost a factor of two amplification of the increase in cloud reflectances that would be expected if cloud liquid water remained constant as the clouds respond to the increases in particle concentrations. The effect of particles on clouds is referred to as the indirect effect of aerosols on climate, or the “Twomey effect” after Shawn Twomey who first suggested the existence of cloud modification by increased particle concentrations. The models produce a wide range of possible outcomes for the indirect effect thereby giving rise to large uncertainties in estimates of the human forcing of the climate system. There is, however, little empirical evidence to support the model results. Though marine stratus represents a relatively simple cloud system, the effects of ships on the overlying stratus provide an almost laboratory-like environment for observing the response of clouds to increased particle loading.

2. Approach

Under the stationary meteorological conditions found during summer months off the west coast of the U.S., marine stratus often show extensive reductions in droplet radii due to the influx of particles emitted by underlying ships. The affected clouds are readily identified by their track-like features in 1-km imagery at near infrared wavelengths. For the AVHRR data analyzed in this study, the tracks appeared as lines in 3.7- μm images of low-level marine stratus. An automated system was developed for identifying 1-km fields of view that were overcast by marine stratus and retrieving the visible optical depths, droplet effective radii, and cloud emission temperatures from the 0.64- μm reflectances and 3.7 and 11- μm radiances measured by the AVHRR. The analysis was restricted to overcast fields of view in order to remove the effects of partial cloud cover on the observed radiances thereby increasing the signal to noise ratio for the indirect effect of the aerosol. A semi-automated scheme was developed to distinguish between clouds polluted by the underlying ship and nearby clouds that were unaffected by the ship. Optical depths, droplet effective radii, and cloud emission temperatures for the polluted and nearby unpolluted clouds were compared to document changes arising from the influx of particles. The methodology and results are described in Coakley and Walsh (2002).

If cloud liquid water is kept constant as the cloud responds to the influx of particles, then the fractional change in the visible optical depth is directly related to the fractional change in the droplet effective radius, as given by

$$\frac{\Delta \tau}{\tau} = -\frac{\Delta R_e}{R_e}, \text{ or equivalently by } -\frac{\Delta \ln \tau}{\Delta \ln R_e} = 1.$$

Ship tracks were analyzed in NOAA-12 and NOAA-14 observations for July 1999 and in NOAA-11 and NOAA-12 observations for June 1994. Over 1800 tracks were analyzed. Owing to the constraints imposed by the retrieval and by the semi-automated scheme for identifying ship tracks, only about a quarter of these tracks yielded 30-km segments that could be used to compare the properties of polluted and nearby unpolluted clouds. In addition, the calibration used for the 0.64- μm reflectances of the NOAA-12 AVHRR proved to be in error (Tahnk and

Coakley, 2002). Observations based on the NOAA-12 AVHRR need to be re-analyzed. The greatest yield of comparisons was obtained for the NOAA-14 July 1999 observations. The 680 tracks analyzed in the NOAA-14 data yielded 136 tracks from which 452 30-km segments were found to be suited for comparisons (Coakley and Walsh 2002).

3. Results

The analysis of the ship tracks in the NOAA-14 AVHRR observations for the U.S. west coast in July 1999 revealed that clouds polluted by ship plumes appeared to lose liquid water when compared with their uncontaminated counterparts. In addition, the analysis resolved discrepancies that had arisen in previous studies of ship tracks, namely that in some studies, the polluted clouds seemed to have excess liquid water, and in others, as was found in the analysis of the NOAA-14 data, the polluted clouds appeared to have less liquid water.

For the July 1999 NOAA-14 observations increases in the visible optical depth, and thus cloud reflectance, in response to the influx of particles were barely detectable. When the analysis was restricted to clouds for which the change in the droplet effective radius was greater than 2 μm , thereby confining the results to the most affected clouds, the ratio of the fractional increase in the visible optical depth to the fractional decrease in droplet effective radius was found to be given by

$$-\frac{\Delta \ln \tau}{\Delta \ln R_e} = 0.46$$

with a 95% confidence range of ± 0.1 . Approximately half of the track segments found to be suitable for analysis had changes in droplet effective radius greater than 2 μm . Clearly, the polluted clouds had higher optical depths, and thus reflected more sunlight than their unpolluted counterparts, as expected for the indirect effect, but the enhancement in reflectivity was considerably less than would have been obtained had cloud liquid water remained constant.

In a few cases, cloud liquid water was enhanced in the polluted clouds. Further analysis revealed that for the 30-km ship track segments in which the polluted clouds had larger liquid water amounts, the tracks were often detectable at visible wavelengths. This finding explains those of previous studies in which ship tracks were identified using reflected sunlight at visible wavelengths. In these earlier studies the polluted clouds were found to contain more liquid water than the unpolluted clouds. Analysis of the NOAA-14 data revealed that tracks which were detectable at visible wavelengths generally had polluted clouds with more liquid water than the surrounding uncontaminated clouds, but such tracks represented only a small fraction of the total number of tracks that were identified using radiances at 3.7 μm . The 3.7- μm radiances reveal the decrease in droplet radius in response to the influx of particles.

Simple radiative transfer calculations were performed to determine whether absorption by particles in the ship plumes might explain the shortfall for the changes in visible optical depths that were interpreted as being caused by a loss of liquid water in the polluted clouds. The amount of particle absorption required to explain the shortfall was orders of magnitude greater

than the amounts that could possibly be generated by ships. Likewise, the analysis of cloud emission temperatures revealed no significant shifts in the cloud top altitudes for the polluted clouds. These results led to the conclusion that the polluted clouds had 15-20% less liquid water than the neighboring unpolluted clouds.

The loss of liquid water in polluted clouds was surprising given the commonly obtained model result that liquid water concentrations increase in clouds affected by an increase in particle burdens. This discrepancy was resolved through the use of a large-eddy simulation model in which clouds were subjected to a range of particle loadings. The results of the simulation model showed that when the analysis was restricted to 1-km scale regions overcast by cloud, then indeed, cloud liquid water was about 15-20% less for the polluted clouds. The model results also showed, however, that over the entire model domain, including both overcast and partially covered 1-km regions, cloud liquid water was conserved during daylight hours. Evidently, in response to the increase in particle concentrations, cloud water was distributed horizontally in the model. When a cloud is polluted, its cloud water extends into cloud-free gaps thereby increasing the cloud cover. Because the liquid water is conserved during daylight hours, expansion of the water into cloud-free regions leaves the overcast fields of view with less liquid water. The satellite observations, which were confined to overcast 1-km fields of view in order to increase the signal to noise ratios for detection of the indirect effect failed to capture any increase in cloud cover within the ship tracks when compared with the fractional cover in the surrounding unaffected clouds. These findings are described in Ackerman et al. (2003).

In addition, the strategy underlying the analysis of ship tracks was that clouds identified as being polluted by ships could be compared with nearby clouds drawn from the same layer that were identical except for the effects of the pollution. The comparison of cloud properties derived from overcast pixels located on opposite sides of the track, however, revealed that the clouds were rather dissimilar, even for pixels separated by only a few kilometers. Autocorrelation lengths for visible optical depths, droplet effective radii, and cloud emission temperatures, were found to be typically less than 10 km (Walsh, 2002; Matheson and Coakley, 2003). That is, even for layered, overcast, marine stratus, clouds separated by as little as 20 km were statistically different. It is this variability that forced the need for a large ensemble of ship track segments in order to detect significant changes in the visible optical depth.

The findings of this study suggest new ways of examining ship tracks in order to determine the limits to which particle pollution will alter the sunlight reflected by clouds. First, in order to improve the signal to noise ratio with which the aerosol indirect effect is determined, properties of polluted clouds must be compared with properties of unpolluted clouds for which the separation distance is small compared with the autocorrelation length (< 5 km). Second, in order to account for the effects of the cloud-free gap filling within polluted clouds, a new scheme for retrieving cloud properties is needed that measures differences in fractional cloud cover within the polluted clouds and the surrounding unpolluted clouds

4. Personnel

Graduate students supported by this grant:

C.D. Walsh, 1 January 1999-31 August 2000. M.S., Atmospheric Sciences, 2002.

M.A. Matheson, 1 January 2001-31 May 2002. Continuing PhD student, Atmospheric Sciences.

G. Luderer, 1 June 2002-31 August 2002. Continuing, M.S. student, Atmospheric Sciences.

Undergraduate student worker supported by this grant:

Jason Cheek, 1 December 2000-31 May 2000. Continuing undergraduate student in Computer Science.

5. Publications and Presentations

Publications and presentations at conferences based on work supported by this grant:

A.S. Ackerman, O.B. Toon, D.E. Stevens, and J.A. Coakley, Jr., 2003: Enhancement of cloud cover and suppression of nocturnal drizzle in stratocumulus polluted by haze. *Geophys. Res. Lett.* (in press).

Coakley, J.A., Jr. and C.D. Walsh, 2002: Limits to the aerosol indirect radiative effect derived from observations of ship tracks. *J. Atmos. Sci.*, **59**, 668-680, 2002.

Coakley, J.A., Jr. and C.D. Walsh, 2001: Limits to the aerosol indirect radiative forcing derived from observations of ship tracks. *AMS Millennium Symposium on Atmospheric Chemistry*. J44-J46.

M.A. Matheson and J.A. Coakley, Jr., 2001: Spatial variability of derived properties for marine stratus clouds. Fall AGU Meeting, San Francisco.

M.A. Matheson and J.A. Coakley, Jr., 2003: Spatial variability of marine stratus as derived from properties retrieved using 1-km AVHRR observations (in preparation).

Tahnk, W.R. and J.A. Coakley, Jr., Improved calibration coefficients for NOAA-12 and NOAA-15 AVHRR visible and near-IR channels. *J. Atmos. Ocean. Tech.* **19**, 1826-1833, 2002.

Walsh, C.D., 2002: Complex signal to noise problem: Determining the aerosol indirect effect from observations of ship tracks in AVHRR data. M.S. Thesis, Oregon State University.

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